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Can osmotic membrane bioreactor be a realistic solution for water reuse?

Gaetan Blandin[1], Pierre Le-Clech[2], Emile Cornelissen[3], Arne R. D. Verliefde[4], Joaquim Comas[1,5] and Ignasi Rodriguez-Roda[1,5]

A growing emphasis on water recycling resulted in intense research activity, aiming to develop and validate reliable and high-quality water treatment processes at lowest cost. In parallel, significant advances in the field of osmotically driven processes have been obtained in the past decade. While the combination of membrane bioreactor (MBR) and reverse osmosis (RO) has become the preferred choice for water reuse, the osmotic membrane bioreactor (OMBR) has begun to be considered as a promising alternative. Based on the current state of knowledge, this paper critically asses the potential for OMBR to be implemented for water reuse application and highlights challenges to reach full scale operation. The initial vision of an energy-free osmotic gradient process is not realistic and its low fouling behaviour is still to be properly assessed. However, OMBR demonstrated unique features such as high rejection of contaminants and an absence of RO brine stream that can support its implementation, especially in the context of high end (potable, industrial) water reuse. However, to become a viable and effective technology for water reuse, significant research and development is still required. Tackling the salinity build-up, developing membranes and modules adapted to OMBR, evaluating long term performance and economics, validating removal of contaminants and developing design, maintenance and automatic control systems constitute critical topics to be considered in future research.

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INTRODUCTION: WATER REUSE CONTEXT

The World Health Organisation and the United Nations have identified wastewater reuse as a key solution to the problem of water scarcity and associated food-related issues and to improper wastewater disposal.[1,2] The global water reuse market is booming (+22% annual growth forecasted for 2014–2019)[3] pushed by the implementation of both non-potable and potable water reuse schemes.[4] Water reuse requires the development and validation of water treatment schemes that can assure safe, high and reliable water quality at competitive costs.[5] Thanks to the early experience gained during the development of water reuse schemes and by transposition from desalination plant technologies, typical potable water reuse trains already emerged. Such schemes generally consist in pursuing wastewater treatment with successive membrane treatment steps (i.e. multi-barrier approach), typically a combination of ultrafiltration (UF) or membrane bioreactor (MBR) and reverse osmosis (RO) followed by a disinfection step.[6] Despite the practical implementation of such schemes, however, a number of challenges remain or are emerging, such as the validation of pathogen removal of the treatment train (log removal credits), the rejection of trace organic contaminants (TrOCs), the monitoring of membrane integrity and the costs of RO brine disposal that require further research and the development of innovative technologies.[6] This paper aims at critically discussing the opportunity for the osmotic MBR (OMBR) to become a future technology for water reuse. Key aspects such as (1) OMBR implementation in water reuse treatment schemes, (2) the potential and need for improved water quality using OMBR-RO, (3) its technical–economical comparison with MBR-RO and (4) the required technical OMBR improvement for full scale operation are discussed in the following sections.

WHERE CAN OSMOTIC MEMBRANE BIOREACTOR BE IMPLEMENTED IN WATER REUSE TRAINS?

OMBR has been developed by analogy with MBR technology.[7] However, instead of using a porous UF or microfiltration (MF) membrane as in MBR systems, a dense forward osmosis (FO) membrane is used and a (draw) solute concentration gradient (also called osmotic pressure differential) acts as the driving force. As a result, permeation of water occurs through the membrane from the lowest (activated sludge suspension) to the highest solute concentration solution (draw solution).[7,8]

In a stand-alone water-recycling train, a reconcentration step (typically RO) is required to extract the purified water and reconcentrate the draw solution that is operated in closed loop. Thus, OMBR can be considered, within a hybrid OMBR-RO system, as an alternative to the more conventional MBR-RO option (Fig. 1). The first studies on OMBR-RO demonstrated interesting properties of the hybrid system:[8,9] (1) two successive dense membrane barriers for reliable production of high quality water, (2) low fouling propensity of OMBR, (3) low fouling in the RO step since the draw solution that must be concentrated is a clean stream (OMBR effluent), (4) no brine production (Fig. 1b).

Another possible configuration is to combine seawater desalination and water reuse (ref. [10] and Fig. 1c) to take advantage of

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[1]LEQUIA, Institute of the environment, University of Girona, Campus Montilivi, Girona, Spain; [2]UNESCO Centre for Membrane Science and Technology, School of Chemical Engineering, The University of New South Wales, Sydney, Australia; [3]KWR Watercycle Research Institute, Post Box 1072, Nieuwegein 3430 BB, The Netherlands; [4]Department of Applied Analytical and Physical Chemistry, Particle and Interfacial Technology Group (PaInT), Ghent University, Faculty of Bioscience Engineering, Gent, Belgium and [5]ICRA, Catalan Institute for Water Research, Parc Scientific and Technologic of The University of Girona, Girona, Spain
Correspondence: Gaetan Blandin (gaetan.blandin@lequia.udg.cat)

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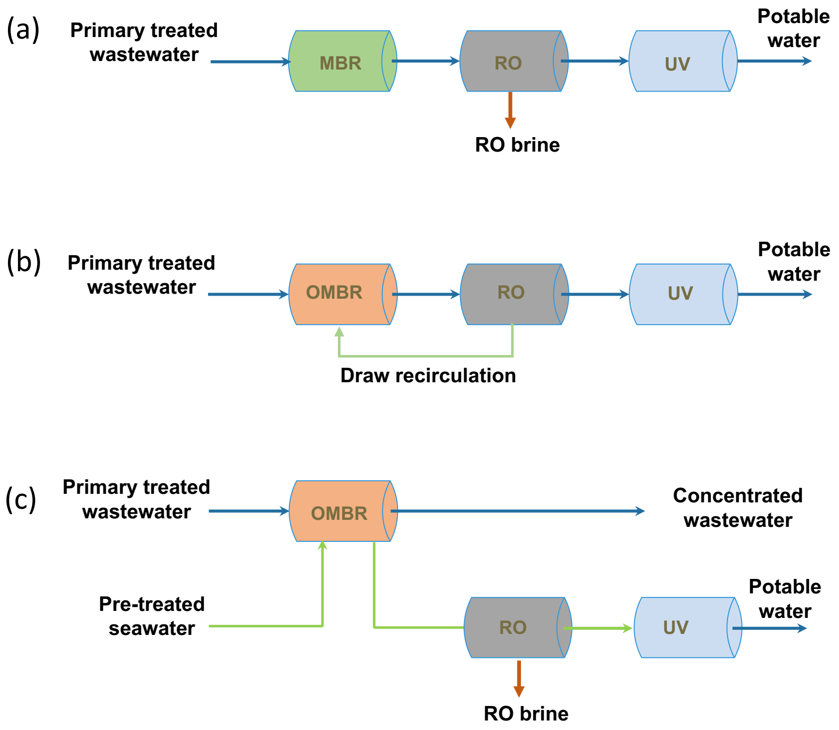

Fig. 1 Schematics of **a** MBR-RO, **b** stand-alone OMBR-RO and **c** OMBR-RO combined with seawater desalination treatment trains in the context of potable water recycling

using seawater as draw solution. In this configuration, diluted seawater requires less energy for the RO step and wastewater pollutants cannot accumulate in the draw loop; however, RO brine is produced and this configuration is limited by the required co-location of the two streams.

CAN OMBR-RO IMPROVE WATER QUALITY AND SAFETY?

Despite exhibiting a double dense barrier membrane system, the critical advantage of OMBR-RO compared to MBR-RO still needs to be demonstrated in terms of improved water quality and process resilience. This will strongly impact the process acceptance by key stakeholders since only significant technological advantages will support its implementation when compared with MBR-RO.

Pathogens removal /system robustness and log removal values

Pathogen removal is a key parameter in water reuse considerations, with several guidelines and frameworks already in place to limit health risks. For example in California, the required overall treatment process log removal values (LRV) for viruses, Giardia and Cryptosporidium are respectively 12, 10 and 10 for potable water reuse.[11] Such high level of removal is difficult to demonstrate with MBR and RO due to the lack of sensitivity of existing on-site process monitoring.[12] Thus, the current limited LRV credit allocated to MF/UF removal of viruses (0) and RO (2)[11] results in the need for intense advanced oxidation processes (AOP) and/or disinfection processes to increase the low LRV affecting costs and producing harmful disinfection by-products.

It could be envisioned that with OMBR-RO and the double dense barrier concept high rejection of pathogens can be obtained[13] but membrane robustness in operation and adapted online monitoring integrity tests still have to be validated to obtain additional LRV credits. The presence of a highly saline (and clean) solution in the draw side facilitates several process monitoring approaches regarding the loss of membrane integrity or selectivity. Monitoring the increase of turbidity in the draw solution or the increase of salinity in the mixed liquor can be envisioned; the addition of a tracer in the draw solution as the *dprShield* with breach-activated barrier proposed by Porifera is also an option to monitor any defect in the process.[14]

TrOCs removal

Due to the porous nature of MF/UF membranes used in MBR, TrOCs (i.e. small organic compounds such as pesticides, pharmaceuticals, endocrine-disrupting chemicals and/or disinfection by-products) are expected to permeate through the membrane.[15] RO allows for a high rejection of most of these compounds but some of the small pollutants are not well rejected. Due to the high retention time of activated sludge in OMBR that allows for enhanced biodegradation[16,17] and its double dense membrane process, OMBR-RO has demonstrated to be very efficient in the removal of most TrOCs.[18] The accumulation of TrOCs in the draw solution loop (and release through RO) observed in FO–RO[19] can be a major limitation for OMBR-RO and should be evaluated and monitored; recalcitrant TrOCs can also accumulate in the mixed liquor. However, the combination of novel generation thin film composite (TFC) membranes with improved TrOCs rejection,[20] the biological degradation occurring in the OMBR (potentially enhanced by enzymatic degradation[21]) and the periodical draw solution replacement can limit TrOCs accumulation in the draw solution. Other configurations such as combined OMBR/MBR (Tackling the salinity build-up section) or water reuse combined with seawater desalination (Fig. 1c) can be also considered to prevent TrOCs accumulation.

WHAT ARE THE NECESSARY OMBR IMPROVEMENTS FOR IMPLEMENTATION?

Developing OMBR modules

Many types of OMBR designs can be envisioned in term of (1) membrane types (hollow fibre (HF), flat-sheet, tubular), (2) arrangement in modules and (3) process configurations (submerged or side stream). So far, spiral wound and plate and frame (pressurised) modules using flat sheet membranes[10] and (pressurised) HF FO modules are commercially available but are not recommended in such sidestream operation due to membrane clogging;[22] tubular FO membranes, usually preferred in these types of applications, are not commercially available yet.[23] Also, those FO modules are not suitable for submerged operation (as preferred in MBR design for urban wastewater treatment), and specific modules dedicated to OMBR need to be developed. HF modules are of great interest but HF membranes with an outer selective layer to prevent permanent fouling need first to be developed.

So far, most OMBR studies have been conducted using cellulose triacetate (CTA) flat sheet FO membrane from HTI company, arranged in home-made setups (either submerged or side stream) leading to permeation flux below 10 L m^{-2} h^{-1}, despite using at least 0.5 M NaCl draw solution concentration.[9] Significant improvement of osmotic pressure efficiency is required for OMBR to become competitive, i.e. by reaching similar operating flux as for MBR (at least 10 L m^{-2} h^{-1}) while reducing significantly the osmotic pressure of the draw solutions (below 10 bar for stand-alone OMBR-RO) in order to limit energy costs for RO draw recovery. The use of novel TFC FO membranes already demonstrated significant flux improvement.[24,25] However, the substantial drop in performance observed when scaling up from cross flow cell to plate and frame submerged module emphasises the crucial importance of module design (hydrodynamics).[26] Submerged OMBR modules have to feature distinct parameters from existing submerged MBR or cross flow modules, especially regarding draw channel design, so as to provide optimised mass transfer as well as membrane support.

Tackling the salinity build-up

Salt accumulation in the OMBR tank, resulting from both the high rejection of dissolved solids (from the wastewater) by the membrane and the reverse salt diffusion (RSD) occurring in the FO process remains a main challenge for OMBR.[27] Salt accumulation can affect the physical and biological properties of the mixed liquor and ultimately the removal efficiency of the process.[16] Typically, non-halophilic organisms usually found in activated sludge processes and MBR, can tolerate salinities up to 10 g L^{-1}.[17] Salinity in the mixed liquor is dependent on the influent salinity, hydraulic and solid retention times (HRT, SRT), forward salt diffusion and RSD. RSD can be mitigated by using novel TFC membranes with improved selectivity or using larger / biodegradable draw solutes; however, the problematics due to the high rejection of salts by OMBR will remain.[28] For typical wastewater salinities of 0.5 g L^{-1} and even in the case of no RSD, the concentration factor SRT/HRT has to be limited below 20 in order to operate with non-halophilic bacteria[17] and possibly down to 10 when accounting for RSD effect in OMBR. These concentration factors, well below the typical range of MBR operation (SRT/HRT above 30), constitute an important limitation of OMBR compared to MBR which can be highly detrimental to OMBR economics, affecting sludge disposal costs and requiring larger OMBR tanks. One alternative is to operate at higher mixed liquor salinity by inoculating halophilic microorganisms. Even if this is a feasible strategy, such system requires even higher draw solution osmotic pressure to allow for sufficient driving force especially considering enhanced external concentration polarisation.

Another proposed solution is to create salt bleeding via the addition of a UF/MF system in parallel to OMBR.[29,30] This process is more complex to operate since two sets of well-balanced membrane systems are required but also offers the advantage of extracting concentrated pollutants or resources which facilitates their further recovery. Among the configurations tested, the (partial) retrofitting of MBR into OMBR can limit investment costs and water production can be adapted to seasonal water needs and to the end user.[31] In combined MBR/OMBR system, the ratio of water produced in both streams, which is crucial in term of water management, will depend on local water needs and flexibility on salinity control.

Developing fouling control and cleaning strategies

Fouling occurrence and control. Low fouling rates observed in early FO/OMBR studies[8,32,33] were (one of) the main motivation(s) for OMBR development. Membrane orientation with active layer facing feed is the most appropriate for severe fouling conditions and is preferred in OMBR.[33] Interestingly, most OMBR studies were conducted using HTI CTA membranes with low permeation fluxes[34] while our recent work demonstrated that with operation at higher flux (above 10 L m^{-2} h^{-1}) a higher fouling rate can be expected.[35] This confirms the presence of a 'critical flux' in FO and the need to study this parameter in OMBR, as it might be as important in optimised MBR operation.[36,37] The development of a dedicated methodology and the comparison of critical flux values of OMBR and MBR and their associated fouling propensities is thus required. Also, since transmembrane pressure (TMP) is not the driving force in OMBR, it is no longer, a relevant indicator to evaluate fouling rate and the need for cleaning in those systems. Most likely OMBR will be operated at constant draw solution concentration; permeation flux will decrease with fouling load. Therefore permeation flux is a relevant indicator for process monitoring and, in a near future, as an automatic closed-loop control parameter, which has proved to be essential in MBR to reduce operational costs.

Fouling mitigation and cleaning. Creating turbulence at the membrane surface either through aeration (air scouring) for submerged systems or through higher cross flow velocities for side stream modules has proven to be efficient for fouling mitigation in FO and MBR systems.[9,33] Backwashing may be of interest for HF or side stream configurations. Relaxation is not adapted to OMBR: stopping the draw pump does not immediately release the osmotic gradient. Osmotic backwashing, which relies on reversing the osmotic gradient so to reverse the flux and detach foulants from the membrane surface, is a fouling mitigation well-adapted to FO.[33] Replacing the draw solution by water or low strength NaOH and HCl solutions assures “cleaning in place” (chemically enhanced) osmotic backwash.[9] Innovative strategies could be envisioned to allow for automatic osmotic backwashing. More evidence is required to determine long term efficiency and feasibility, frequency of cycles and impact on membrane ageing.

As for MBR, a membrane cleaning strategy outside the OMBR tank may be required for submerged modules. Common MBR chemical cleaning agents (acidic, alkaline, chlorine based) cannot be used due to the low tolerance to extreme pH and chlorine of TFC FO membranes. Again, osmotic backwashing can be a more suitable strategy. In this case, water is circulated in the draw channel and the membrane module/skid is submerged in a higher salinity solution. Osmotic backwashing is followed by simply rinsing the membrane with water so as to remove the foulant cake and the salts still present on the membrane surface.[9,38]

Evaluating membrane resistance and management of unexpected breakage

FO membranes are not only thinner than MF/UF membranes but also their separation properties rely entirely on their thin active layer facing the challenging activated sludge. A few studies already demonstrated that membrane degradation occurs during long term OMBR operation, leading to a loss of selectivity for both CTA and TFC membranes.[24,39] Biodegradation, physical defects and chemical modifications were hypothesised as potential causes but more studies are required to determine the causes and identify also the potential impact of mechanical constraints, chemical attack and abrasion. This is a key question as it may impact process stability and membrane replacement rate and point out the required development of tailor-made membranes for OMBR.

Another potential unexpected event is the loss of membrane integrity or material failure, leading to a salt leakage from the draw solution into the mixed liquor and/or pollution of the draw solution. A salinity shock is to be avoided to protect the biological system from irreversible damage; early detection of leaks would be crucial for process validation in potable reuse. As it has happened in MBR operation, new developments on automation and automatic control are expected to reduce costs while increasing robustness for OMBR operation.[40]

CAN OMBR-RO BE FINANCIALLY COMPETITIVE?

Carrying out a thorough technical economic evaluation of OMBR-RO is critical to estimate if OMBR-RO can be competitive and in which contexts. At this stage of OMBR development, only initial assumptions can be made and specific focus points to be optimised and assessed are summarised in Table 1.

Table 1 observations also apply to OMBR-RO combined with desalination for all aspects regarding the OMBR operation. However, since seawater is used as draw solution, there are no costs of draw replenishment (#5 in Table 1) and obtaining a competitive flux is less challenging (9). Thanks to the lower salinity of the seawater entering the RO, lower operating pressure and/or higher recovery can be obtained depending on the envisioned water scenario.[41] Brine management costs (#6 and 10 in Table 1) apply but are largely mitigated thanks to the joint disposal with

Table 1. Initial assumption of potential economics advantage and drawbacks of OMBR/RO in comparison with MBR-RO

Investment costs	
1) Membrane module footprint	OMBR modules are still to be developed (Developing OMBR modules section). Assuming similar design as MBR and similar permeation flux at OMBR maturity, membrane modules footprint is expected to be similar for OMBR and MBR
2) Membrane module costs	Assuming similar module designs (Developing OMBR modules section), module costs are highly dependent from the membrane production costs. Current high production costs of FO membranes will be reduced with larger scale production[42]
3) OMBR tank footprint	Similar to MBR since high removal efficiency with similar HRT, SRT, nutrient loading, and mixed liquor concentration as common MBR values were observed.[34] Salinity build-up in OMBR is a major issue still to be overcome and that can have some impact on SRT and overall process design (Tackling the salinity build-up section)
4) RO unit	Similar RO investment costs can be envisioned for MBR-RO and OMBR-RO systems since similar amounts of water are produced. Final design and refined assessment have to integrate the draw type and concentration and the required operating pressure. Benefits can be expected from the lower fouling propensity of a clean OMBR draw solution
5) Draw replenishment	A draw solution dosing system is required for OMBR-RO in order to compensate for draw solution losses
6) RO brine management	No RO brine produced with OMBR-RO; significant savings can be envisioned vs. MBR-RO (tanks, pumps, conveyance, and RO brine concentration processes). Brine treatment costs are very site specific but avoided cost could be as high as 0.6€ m^{-3} for zero liquid discharge[11]
Energy	
7) Permeate extraction	OMBR do not require transmembrane pressure but energy is required for draw circulation. Only marginal gains are expected since low-hydraulic pressure is used in MBR
8) Aeration	Lower OMBR fouling propensity can be translated in less air scouring, i.e. lower energy needs. However, a higher fouling rate is expected with novel FO membranes operating at higher flux. Large scale testing is required to refine that critical aspect
9) RO operating pressure	A major cost of water reuse trains (around 0.2€ m^{-3}) for typical operation at 10 bar[6]. Thus, a key challenge to be competitive is to operate OMBR-RO with maximum RO pressure of 10 bar, i.e. draw osmotic pressure below 10 bar, while assuring permeation range similar to MBR (Developing OMBR modules section)
10) RO brine management	Energy costs for RO brine management in existing water reuse schemes can be extremely high both in case of pumping for conveyance or concentration.[11] OMBR-RO closed loop operation without brine production is a key advantage
Maintenance	
11) Draw replenishment costs	Replenishment costs associated with draw solution losses through FO and RO membranes can be significant.[43] However, improvement of membranes selectivity and optimisation of draw solutions already allowed to decrease those costs down to 0.02€ m^{-3}[44]
12) Fouling/ cleaning OMBR:	Lower fouling tendency of OMBR can lead to savings in cleaning costs (reagents and downtime operation). To be refined through full scale operation in similar MBR/OMBR flux conditions and after validation of adapted leaning strategies (Developing fouling control and cleaning strategies section)
13) Fouling /cleaning RO	Both the FO permeate and the draw solution are clean solutions and therefore very limited fouling is expected on the RO side of OMBR-RO. Significant advantage versus MBR-RO in term of cleaning costs (chemicals) and RO process stability[18]
14) OMBR sludge management	Salinity build-up in OMBR may lead to operation at lower SRT and consequently increases sludge production and/or salinity. Impact on sludge disposal costs is to be evaluated
15) Membrane replacement	Long term resistance of FO membrane is still to be evaluated; few studies already indicate membrane degradation over short time of experiment (Developing OMBR modules section). Membrane replacement rate can be evaluated only through extended pilot/full plant testing
16) AOP/disinfection	Treatment costs/dosage can be decreased due to the improved removal of pathogens and TrOCs and potential additional LRV credit

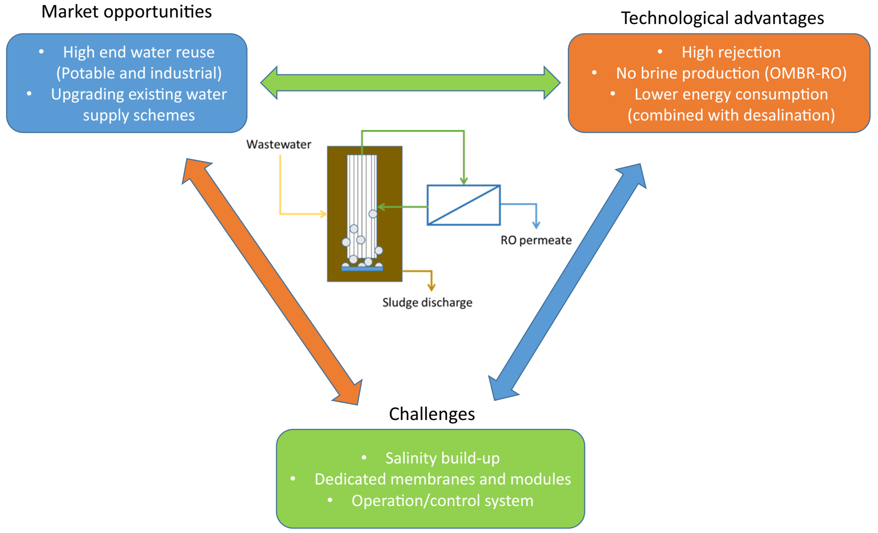

Fig. 2 Opportunities, technological advantages and challenges for OMBR

usual RO brine. In combined OMBR/MBR operation, additional investment/operational costs due the operation of two systems are expected but can be balanced by avoided sludge management costs (#14), flexibility in water management and MBR retrofitting.

OUTLOOK: CHALLENGES AND PERSPECTIVES

Recent literature shows that the initial FO/OMBR technical and economic potential (i.e., free osmotic gradient energy process with low fouling behaviour) may be limited. However, generated evidence that OMBR has high rejection of contaminants and limited brine production can warrant OMBR-RO implementation, especially in the context of high end (potable, industrial…) water reuse. Apart from the technical challenge of salinity build-up, developing membranes and modules adapted to OMBR, full scale validation of OMBR-RO schemes and setting up maintenance and control tools are important issues to be considered in future research, as they can largely impact OMBR economics (Fig. 2).

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AUTHOR CONTRIBUTIONS

The writing of this manuscript was led by G.B. All co-authors have made substantial contributions in the design, writing and successive revisions of the manuscript.

ADDITIONAL INFORMATION

Competing interests: P.L.-C. and A.R.D.V. certify that they have NO potential conflict of interest that they should disclose. G.B., J.C. and I.R.-R. disclose that they are listed as inventor of the patent application PCT/EP2017/064605 related to the retrofitting of MBR in OMBR. E.C. discloses that he is listed as inventor of the Dutch Patent NL1028484, Priority date 8-3-2005 related to the operation and design of the OMBR.

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